Suzaku search for evidence of sterile neutrinos in the Ursa Minor dwarf spheroidal galaxy

Michael Loewenstein

NASA/GSFC, Code 662, Greenbelt, MD 20771, USA
University of Maryland, College Park Department of Astronomy and CRESST

Abstract. We present results of our search for X-ray line emission associated with the radiative decay of the sterile neutrino, a well-motivated dark matter candidate, in *Suzaku* Observatory spectra of the Ursa Minor dwarf spheroidal galaxy. These data represent the first deep observation of one of these extreme mass-to-light systems and the first dedicated dark matter search using an X-ray telescope. No such emission line is positively detected; and, we derive new upper limits that match or approach the best previous results over the entire 1–20 keV mass range from a single *Suzaku* observation. These are used to place constraints on the existence of sterile neutrinos with given combinations of mass and active-sterile neutrino oscillation mixing angle in the general case, and in the case where they are assumed to constitute all of the dark matter. The allowed range implies that sterile neutrinos remain a viable candidate to make up some – or all – of the dark matter and also explain pulsar kicks and various other astrophysical phenomena.

Keywords: sterile neutrinos, dark matter
PACS: 95.35.+d, 95.85.Nv, 98.52.Wz, 98.62.Ck, 14.60.St, 12.60.-i

CONTEXT AND MOTIVATION

The observational evidence that nonbaryonic dark matter comprises most of the mass in the universe is extremely strong, but the nature of dark matter remains a mystery. No particle included in the Standard Model has the characteristics required to explain dark matter; and, new physics will emerge with the identification of the dark matter particle. The recent discovery that neutrinos have mass is most easily accommodated by adding right-handed or *sterile neutrinos* to the Standard Model. The so-called Majorana masses of these neutrinos are unknown parameters. If one of the sterile neutrinos has mass in the 1–20 keV range and has small mixing angles with the active neutrinos (as expected), such a particle is a plausible candidate for dark matter [1]. The same particle could be produced in a supernova explosion, and its emission from a cooling neutron star could explain the pulsar kicks. [2, 3, 4, 5], could facilitate core collapse supernova explosions [6, 7] and can affect the formation of the first stars [8, 9] and black holes [10, 11]. See the contribution of A. Kusenko for more details on the physics and astrophysics of sterile neutrinos.

Clearly there is a strong motivation to search for signatures of sterile neutrinos in the keV mass range. The most promising way to discover (or rule out) relic sterile neutrinos is with the use of X-ray telescopes. The sterile neutrinos can decay radiatively [12, 13] and produce a lighter neutrino and a photon amenable to X-ray observation [14, 15, 17]. Since this is a two-body decay, a line is expected in the X-ray spectrum. There is an interesting regime in which sterile neutrino radiative decay may be detectable by X-ray

CP1166, *Sources and Detection of Dark Matter and Dark Energy in the Universe,*
edited by D. B. Cline

instruments *presently* in orbit.

WHERE TO LOOK AND WHAT TO LOOK WITH – *SUZAKU* OBSERVATIONS OF DWARF SPHEROIDAL GALAXIES

Local group dwarf spheroidal galaxies are ideal targets because of their proximity, high dark matter density [18], and absence of additional obscuring sources such as hot X-ray emitting plasma, X-ray binaries, and active nuclei. Based on their average dark matter surface densities, the Ursa Minor and Draco dwarf spheroidals are the optimal systems for large field-of-view X-ray spectroscopic investigation.

The *Suzaku* Observatory [19] provides the most sensitive instruments for current searches for weak sterile neutrino radiative decay lines in the $\sim 0.5-10$ keV bandpass, because of its low and stable background [20], and the relatively sharp spectral resolution of its CCD spectrometers [21, 23]. At the time of observation, three co-aligned, $17.8' \times 17.8'$ field-of-view X-ray Imaging Spectrometer (XIS) CCD cameras [21] – two front-illuminated (FI: XIS0 and XIS3) and one back-illuminated (BI: XIS1) – were operational. The BI chip is more sensitive below 1 keV but has a much higher internal background, especially above 7 keV; so, that BI and FI CCDs complement each other for broad-band studies. Each XIS lies in the focal plane of an X-ray Telescope (XRT) with a $2'$ half-power diameter [24]. We were awarded $\sim$ 70 ksec of *Suzaku* Cycle 2 observatory time to study each of these systems. These data represent the first deep observations of these extreme mass-to-light systems, and the first dedicated dark matter search using an X-ray telescope. In this paper, we discuss our analysis of *Suzaku* observations of the Ursa Minor system and the resulting constraints on sterile neutrinos [22].

HOW TO LOOK – *SUZAKU* SPECTRAL ANALYSIS

Observations were conducted utilizing the space-row charge injection (SCI) technique that reverses the degradation in energy resolution caused by accumulated radiation damage. We initiate our analysis by reprocessing the unfiltered event files, and then produce cleaned photon lists that account for the effects of SCI. Source and particle background spectra are extracted from all three active chips, excluding an $8'$ diameter circular region centered on the one bright point source in the field. Spectral redistribution matrices and effective area functions are generated based on the characteristics and configuration of the optics and instruments. The spectra from the FI chips, XIS0 and XIS3, are co-added and a weighted XIS0+3 response function calculated.

Since dwarf spheroidal galaxies are intrinsically weak X-ray emitters, their X-ray spectra are dominated by internal and astrophysical background components. These consist of Non-X-ray charged particle Background (NXB), Galactic X-ray Background (GXB), and (extragalactic) Cosmic X-ray Background (CXB). The NXB component is estimated from night earth observations taken in SCI mode within 150 days of the starting or ending dates of the Ursa Minor observation [20]. The GXB may be characterized

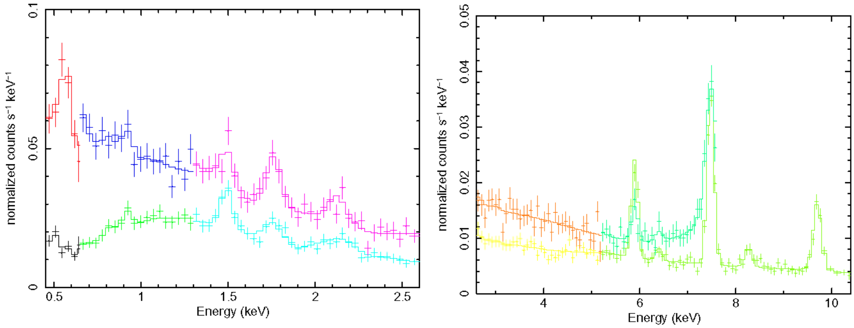

FIGURE 1. Low-energy (< 2.6 keV; **above**) and high energy (> 2.6 keV; **below**) XIS0+3 and XIS1 spectra; the XIS1 spectrum has the higher count rate. Each spectrum is divided into 5 segments, delineated here by different colors, and all ten segments are simultaneously fit. Histograms trace the best fit model.

by a two-temperature thermal plasma corresponding to 0.22 keV temperature halo and 0.075 keV local hot bubble contributions, the CXB by an index 1.45 power-law.

We apply a maximum likelihood analysis to fitting the unsubtracted spectra (Figure 1) that, along with the lack of intrinsic X-ray emission, enables us to minimize systematics, and account for those that remain. There are no *a priori* assumptions about the accuracy of the NXB estimate that we only use to set model line energies and shapes, or whether an extra line feature lies above or below the total continuum. This approach also allows us to consider sterile neutrino masses up to ~ 20 keV, which is not possible with analysis of the background-subtracted spectra. Best-fits to null-hypothesis models (*i.e* those *without* an *extra* emission line from sterile neutrino radiative decay) of the total spectra are determined through minimization of the maximum likelihood Cash statistic (C-statistic; Cash 1979). We perform Monte Carlo spectral simulations of the null model to derive the experimental cumulative probability distribution, $P(<\Delta C)$, at each putative line energy in the *Suzaku* bandpass, $E_{\rm line}$. $\Delta C \equiv C_{\rm null} - C_{\rm line}(E_{\rm line})$, where $C_{\rm null}$ and $C_{\rm line}(E_{\rm line})$ are the minimized fit statistics for the null model and null-plus-line-at-$E_{\rm line}$ models, respectively. Our upper limits are those that correspond to a change in the C-statistic in fits to the actual spectra that occurred in 1% of our Monte Carlo simulations.

RESULTS: LIMITS ON STERILE NEUTRINOS

The line flux ($F_{\rm line}$) limits we derive, are converted to limits on the radiative decay width, $\Gamma_{\nu_s \to \gamma \nu_a} = 10^{-27}\Gamma_{-27}$ s^{-1} as a function of decay photon energy E_γ and, in turn, to constraints on the combination of sterile neutrino mass, $m_{\rm st} = 2E_\gamma$, mixing angle, θ, and abundance (relative to the total amount of dark matter in the universe), $f_{\rm st}$, from the following relations:

$$\Gamma_{\nu_s \to \gamma \nu_a} = \frac{9}{256\pi^4}\, \alpha_{\rm EM}\, {\rm G_F^2}\, \sin^2\theta\, m_{\rm s}^5$$

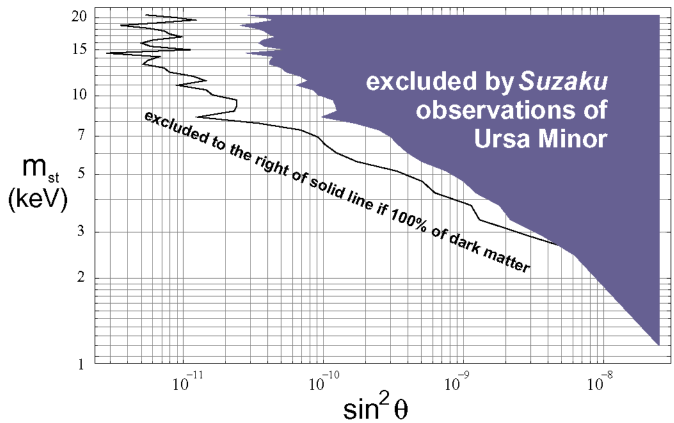

FIGURE 2. The sterile neutrino parameter space to the right of the solid curve is excluded by the *Suzaku* observation of Ursa Minor if dark matter is solely composed of sterile neutrinos produced by some (unspecified) mechanism. The solid exclusion region is model-independent, based only on the assumption of the standard cosmological history below the temperature of a few hundred MeV, when the DW production by neutrino oscillations takes place.

$$= \frac{1}{1.8\times10^{31}\,\mathrm{s}}\left(\frac{\sin^2\theta}{10^{-10}}\right)\left(\frac{m_s}{\mathrm{keV}}\right)^5, \tag{1}$$

and

$$F_{\rm line} = 1.1\times10^{-4}\,\Gamma_{-27} f_{\rm st} M_7 d_{100}^{-2}\left(\frac{\mathrm{keV}}{m_{\rm st}}\right)\ \mathrm{cm^{-2}\,s^{-1}} \tag{2}$$

$$= 6.2\times10^{-9}\left(\frac{\sin^2\theta}{10^{-10}}\right)\left(\frac{m_{\rm st}}{\mathrm{keV}}\right)^4 f_{\rm st} M_7 d_{100}^{-2}\ \mathrm{cm^{-2}\,s^{-1}}, \tag{3}$$

where $\alpha_{\rm EM} = 1/137.0$ and $G_{\rm F} = 1.2\times10^{-5}\mathrm{GeV}^{-2}$. The dark matter mass in projection, $10^7 M_7\ \mathrm{M}_\odot$, is derived from stellar dynamics [18, 26].

We derive two different limits that address the following: (1) whether the existence of a sterile neutrino with a given mass and mixing angle is consistent with standard cosmological history, and (2) whether sterile neutrinos of a given mass and mixing angle can account for 100% of dark matter.

For the first limit, we assume the Dodelson-Widrow (DW) production mechanism through non-resonant oscillations which gives the minimal abundance of sterile neutrinos in standard Big Bang cosmology. Using the minimal rate of DW production consistent with the results of [16] to eliminate $f_{\rm st}(m_{\rm st},\theta)$ in equation 3, which provides the most conservative constraints, we derive the exclusion region shown in Figure 2. This region is excluded regardless of the physics responsible for mass generation of neutrinos, or any other physics beyond direct mixing between sterile and active neutrinos, and provides the most conservative constraints.

For the second kind of limit, we determine the part of parameter space for which sterile neutrinos can account for all the cosmological dark matter, while still being

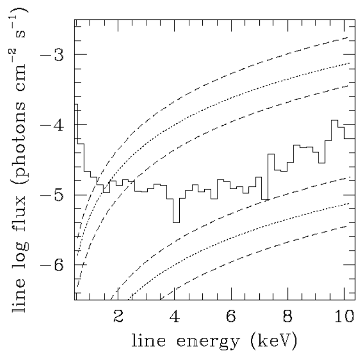

FIGURE 3. Line flux upper limits and $f_{st} = 1$ (upper curves) and $f_{st} = 0.1$ (lower curves) DW predictions for maximum, average, and minimum production [16].

consistent with *Suzaku* observations. This is derived by setting $f_{st} = 1$ in equation 2, without reference to any specific production mechanism. The corresponding excluded region is delineated by the solid line in Figure 2.

One can ask which dark matter particle mass in the form of sterile neutrinos, for $f_{st} = 1$, produced solely by the DW mechanism is consistent with *Suzaku* observations. Here one can set an upper limit on the sterile neutrino mass: $m_{st} < 2.5$ keV. However, the DW mechanism with $f_{st} = 0.1$ is not ruled out at any energy covered by the *Suzaku* spectra ($\sim 1-20$ keV). This is shown in Figure 3, where our line flux upper limits are compared with the DW predictions.

SUMMARY AND FUTURE PROSPECTS

With a single *Suzaku* observation of the Ursa Minor dwarf spheroidal, we have derived limits on the mass and mixing angle of the sterile neutrino dark matter candidate that are comparable to, or better than, previous constraints over the entire 1–20 keV mass range from a single *Suzaku* observation. These limits are illustrated in Figure 2 for the case where sterile neutrinos comprise all of the dark matter regardless of how they are produced in the early universe, and in the more general case, when their abundance is not assumed, but is calculated under the assumptions that minimize it. If solely produced by the DW mechanism, sterile neutrinos cannot constitute 100% of the dark matter in Ursa Minor unless they are less massive than 2.5 keV. The allowed range implies that sterile neutrinos remain a viable candidate to make up some – or all – of the dark matter and also explain pulsar kicks and various other astrophysical phenomena.

As the *Suzaku* NXB characterization improves, it may be possible to tighten upper limits in the $m_{st} > 2$ keV regime; at lower masses the ubiquity of the GXB will remain a barrier until significantly higher energy resolution is attained – e.g. with *Astro-H*.

[1] Since there is some uncertainty as to the dynamical state of dwarf spheroidals on an individual basis, X-ray constraints obtained from additional systems are warranted (e.g., our paper – in preparation – on the *Suzaku* observation of the Draco system). The Sloan Digital Sky Survey (SDSS) has approximately doubled the number of galaxies identified with the local group population and revealed a new sub-population of faint Milky Way satellites [27], including some with very high mass-to-light ratio [18, 26] that are intriguing targets for future investigation. Finally, predictions of the Lyα forest power spectrum in fully self-consistent large scale structure simulations with sterile neutrinos can provide complementary constraints in the form of a lower limit on the particle mass.

ACKNOWLEDGMENTS

This research has made use of data obtained from the Suzaku satellite, a collaborative mission between the space agencies of Japan (JAXA) and the USA (NASA). This work was supported by NASA grants NNXO8AD96G and NNX07AO94G.

REFERENCES

1. Dodelson, S. & Widrow, L. M. 1994, Phys. Rev. Lett., 72, 17
2. Kusenko, A., & Segrè, G. 1997, Phys. Lett. B, 396, 197
3. Fuller, G. M., Kusenko, A., Mocioiu, I., & Pascoli, S. 2003, Phys. Rev. D, 68, 103002
4. Kusenko, A. 2004, J. Mod. Phys. D, 13, 2065
5. Kusenko, A., Mandal, B. P., & Mukherjee, A. 2008, Phys. Rev. D, 77, 123009
6. Fryer, C. L., & Kusenko, A. 2006, ApJS, 163, 335
7. Hidaka, J. & Fuller, G. M. 2007, Phys. Rev. D, 76, 083516
8. Biermann, P. L., & Kusenko, A. 2006, Phys. Rev. Lett., 96, 091301
9. Stasielak, J., Biermann, P. L., & Kusenko 2007, ApJ, 654, 290
10. Munyaneza, F., & Biermann, P. L. 2005, A& A, 436, 805
11. Munyaneza, F., & Biermann, P. L. 2006, A& A, 458, L9
12. Pal, P. B., & Wolfenstein, L. 1982, Phys. Rev. D, 25, 766
13. Barger, V., Phillips, R. J. N., & Sarkar, S. 1995, Physics Letters B, 356, 617
14. Abazajian, K., Fuller, G. M., & Patel, M. 2001, Phys. Rev. D, 64, 023501
15. Abazajian, K., Fuller, G. M., & Ticker, W. H. 2001, ApJ, 562, 593
16. Asaka,, T., Shaposhnikov, M., & Laine, M. 2007, JHEP, 01, 091
17. Dolgov, A. D., & Hansen, S. H. 2002, Astroparticle Physics, 16, 339
18. Strigari, L. E., et al. 2008, ApJ, 678 614
19. Mitsuda, K. et al. 2007, PASJ, 59, S1
20. Tawa, N., et al. 2008, PASJ, 60, S11
21. Koyama, K., et al. 2007, PASJ, 59, S23
22. Loewenstein, M., Kusenko, A., & Biermann, P. L. 2008, ApJ, submitted (astro-ph/0812.2710)
23. Nakajima, H., et al. 2008, PASJ, 60, S1
24. Serlemitsos, P. J., et al. 2007, PASJ, 59, S9
25. Cash, W. 1979, ApJ, 228, 939
26. Strigari, L. E., et al. 2008, Nature, 454, 1096
27. Belokurov, V., et al. 2007, ApJ, 654, 897

[1] `http://www.isas.ac.jp/e/enterp/missions/astro-h/`